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(54) Title: POWER IQ MODULATION SYSTEMS AND METHODS

(57) Abstract

Power IQ modulations systems and methods include first and second power amplifiers, each including a signal input, a supply input and a power input. The first and second power amplifiers are preferably class–C power amplifiers. A source of first, second, third and fourth reference frequency signals is also provided. The first and second reference frequency signals are inverted relative to one another, and the third and fourth reference frequency signals are inverted relative to one another. Preferably, the first, second, third and fourth reference frequency signals are 0°, 180°, 90° and 270° phase shifted reference frequency signals, respectively. A switching system is also provided that selectively applies one of the first and second reference frequency signals to the signal input of the first power amplifier as a function of the polarity of one of the I and Q input signals. The switching system also selectively applies one of the third and fourth reference frequency signals to the signal input of the second power amplifier as a function of the polarity of the other of the I and Q input signals. A third amplifier, preferably a class–D amplifier, is responsive to the one of the I and Q input signals to supply a first variable supply voltage to the supply input of the first amplifier. A fourth amplifier, also preferably a class–D amplifier, is responsive to the other of I and Q input signals to supply a second variable supply voltage to the supply input of the second amplifier. A coupler couples the power outputs of the first and second power amplifiers to a load such as a radiotelephone antenna. Accordingly, power IQ modulation is provided that can use class–C and class–D amplifiers that are highly efficient.

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POWER IQ MODULATION SYSTEMS AND METHODS

Field of the Invention

This invention relates to modulation systems and methods, and more particularly to IQ modulation systems and methods.

Background of the Invention

Modulation systems and methods are widely used in transmitters to modulate information including voice and/or data onto a carrier. The carrier may be a final carrier or an intermediate carrier. The carrier frequency can be in UHF, VHF, RF, microwave or any other frequency band. Modulators are also referred to as "mixers" or "multipliers". For example, in a mobile radiotelephone, a modulator is used for the radiotelephone transmitter.

Figure 1 illustrates a conventional IQ modulator. As shown in Figure 1, an IQ modulator **10**, also referred to as a "quadraphase modulator" or a "quadrature modulator" includes a quadrature splitter **20**, also known as a 90° phase shifter, and a pair of multipliers **16a, 16b** coupled to the quadrature splitter. A controlled oscillator **15**, such as a Voltage Controlled Oscillator (VCO), is coupled to the quadrature splitter **20** to produce 90° phased shifted oscillator signals. In-phase (I) data **11a** and quadrature-phase (Q) data **11b** are coupled to a respective multiplier or mixer **16a, 16b**. Digital input data is converted to analog data by I Digital-to-Analog Converter (DAC) **14a** and Q DAC **14b**, respectively. The outputs of the respective DACs **14a** and **14b** are applied to the respective low pass filters **12a** and **12b** to provide the respective I and Q data inputs **11a** and **11b**. The modulator modulates the input data on a carrier **13**, by summing the outputs of the multipliers **16a, 16b** at a summing node **218**. The modulated carrier is amplified by a power amplifier **22** and transmitted via an antenna **24**.

In modern radiotelephone communications, mobile radiotelephones continue to decrease in size, cost and power consumption. In order to satisfy these objectives, it is generally desirable to provide IQ modulation systems and methods that can

provide high power modulation while reducing the amount of battery power that is consumed. Unfortunately, the power amplifier 22 of an IQ modulator may consume excessive power due to efficiency limitations therein. More specifically, it is known to provide a linear class-A or class-AB power amplifier 22 that may have efficiencies as low as 30 percent or less. Thus, large amounts of battery power may be wasted as heat. Moreover, the noise figure of a conventional IQ modulator may be excessive so that high cost Surface Acoustic Wave (SAW) filters may need to be used.

It is also known to separately modulate the amplitude and phase of an input signal using an "rTheta" technique. In the rTheta technique, the phase is modulated at the oscillator, and the amplitude is modulated at the power amplifier stage. Unfortunately, the rTheta technique may require the oscillator phase lock loop to support the phase modulation bandwidth. With wide bandwidth radiotelephone signals such as TDMA and CDMA signals, it may be increasingly difficult to provide the requisite bandwidth in the oscillator phase lock loop.

Summary of the Invention

It is therefore an object of the present invention to provide improved IQ modulation systems and methods.

It is another object of the present invention to provide IQ modulation systems and methods that can provide high efficiency.

It is still another object of the present invention to provide IQ modulation systems and methods that do not require the use of linear amplifiers.

These and other objects are provided, according to the present invention, by providing power IQ modulation systems that modulate in-phase (I) and quadrature-phase (Q) input signals in the power amplifiers themselves. High efficiency class-C and class-D power amplifiers may be used.

Power modulation systems according to the present invention include first and second power amplifiers, each including a signal input, a supply voltage input and a power output. The first and second power amplifiers are preferably class-C power amplifiers. A source of first, second, third and fourth reference frequency signals is also provided. The first and second reference frequency signals are inverted relative to one another, and the third and fourth reference frequency signals are inverted relative to one another. Preferably, the first, second, third and fourth reference

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frequency signals are 0°, 180°, 90° and 270° phase shifted reference frequency signals, respectively.

A switching system is also provided that selectively applies one of the first and second reference frequency signals to the signal input of the first power amplifier as a function of the polarity of one of the I and Q input signals. The switching system also selectively applies one of the third and fourth reference frequency signals to the signal input of the second power amplifier as a function of the polarity of the other of the I and Q input signals.

A third amplifier, preferably a class-D amplifier, is responsive to the one of the I and Q input signals to supply a first variable supply voltage to the supply input of the first amplifier. The supply voltage input preferably corresponds to the drain or collector voltage of the output stage of the first amplifier. A fourth amplifier, also preferably a class-D amplifier, is responsive to the other of I and Q input signals to supply a second variable supply voltage to the supply input of the second amplifier. A coupler couples the power outputs of the first and second power amplifiers to a load such as a radiotelephone antenna. Accordingly, power IQ modulation is provided that can use class-C and class-D amplifiers that are highly efficient.

The first, second, third and fourth reference frequency signals may be generated by a controlled oscillator that produces the first reference frequency signal. A first inverter is responsive to the controlled oscillator to produce the second reference frequency signal. A phase shifter is responsive to the controlled oscillator to produce the third reference frequency signal. A second inverter is responsive to the phase shifter to produce the fourth reference frequency signal.

The switching system may include a first switch that is responsive to the one of the I and Q input signals being positive, to couple the first reference frequency signal to the first power amplifier. The first switch is also responsive to the one of the I and Q input signals being negative, to couple the second reference frequency signal to the first power amplifier. A second switch is responsive to the other of the I and Q input signals being positive, to couple the third reference frequency signal to the second power amplifier. The second switch is also responsive to the other of the I and Q input signals being negative to couple the fourth reference frequency signal to the second power amplifier. A first polarity detector may be provided, that is coupled between the one of the I and Q input signals and the first switch, to detect whether the

one of the I and Q input signals is positive or negative. A second polarity detector may also be provided, that is coupled between the other of I and Q input signals and the second switch, to detect whether the other of the I and Q input signals is positive or negative.

A first analog-to-digital converter also may be coupled between the one of the I and Q input signals and the third amplifier, such that the third amplifier is responsive to a digital representation of the one of the I and Q signals to supply a first variable supply voltage to the supply input of the first amplifier. A second analog-to-digital converter also may be provided, that is coupled between the other of the I and Q input signals and the fourth amplifier, such that the fourth amplifier is responsive to a digital representation of the other of the I and Q signals to supply a second variable voltage supply to the supply input of the second amplifier. The analog-to-digital converters are preferably delta-sigma analog-to-digital converters.

Various embodiments of couplers that couple the power outputs of the first and second power amplifiers to the load may also be provided. The coupler may include a matching network that couples the first and second power amplifiers to a load such as a radiotelephone antenna. The coupler preferably isolates the first and second power amplifiers from one another while coupling the first and second power amplifiers to the load. The coupler may include a first quarter wavelength transmission line that couples the first power amplifier to the matching network and a second quarter wavelength transmission line that couples the second power amplifier to the matching network. In a non-preferred but nevertheless useful implementation, the coupler may include a first isolator that couples the first power amplifier to the matching network and a second isolator that couples the second power amplifier to the matching network. The matching network may also be a voltage-to-current converting matching network, such as a quarter-wave transmission line or discrete component equivalent thereof. These coupling techniques also are illustrated in Application Serial No. 09/054,063, filed April 2, 1998, entitled *"Hybrid Chireix/Doherty Amplifiers and Methods"* to the present co-inventor Dent assigned to the assignee of the present invention, the disclosure of which is hereby incorporated herein by reference, and Application Serial No. 09/054,060, filed April 2, 1998 entitled *"Power Waveform Synthesis Using Bilateral Devices"* to the present co-inventor Dent, assigned to the assignee of the present invention, the disclosure of which is hereby incorporated herein by reference.

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Finally, it is known that the first and second class-C amplifiers may have a nonlinear amplitude and/or phase response as a function of the respective first and second variable supply voltages. Power modulation according to the invention may include amplitude distortion and phase distortion compensation that is responsive to the I and Q input signals, to modify the I and Q input signals to reduce the nonlinear amplitude response. In particular, compensation systems and methods are responsive to the I and Q input signals, to generate predistorted I and Q signals, and to apply the predistorted I and Q signals to the switching system and to the third and fourth amplifiers, to thereby compensate for the nonlinear distortion.

More specifically, a lookup table may be provided that is responsive to the I input signal, to produce a first amplitude distortion compensating value and a first phase compensating value, and that is responsive to the Q input signal to produce a second amplitude distortion compensating value and a second phase compensating value. A pair of lookup subtables may also be provided. A summer is also provided that adds the first amplitude distortion compensating value and the second phase compensating value to produce the predistorted I signal, and that subtracts the first phase compensating value from the second amplitude distortion compensating value, to produce the predistorted Q signal. A separate adder and subtractor also may be provided. Compensation systems and methods according to the invention also may be used separately to precompensate for distortion in an amplifier that produces distortion.

Accordingly, the present invention can provide power IQ modulation at high efficiency to thereby allow reduced size, cost and/or power consumption of a mobile radiotelephone or other transmitter. Wide bandwidth oscillator phase lock loops need not be used, and high performance SAW filters may not be needed to reduce transmitted noise. Associated power modulation methods are also provided.

Brief Description of the Drawings

Figure 1 is a block diagram of a conventional IQ modulator.

Figures 2-5 are block diagrams of power IQ modulation systems and methods according to the present invention.

Figure 6 is a block diagram of compensation systems and methods according to the present invention.

Detailed Description of Preferred Embodiments

The present invention now will be described more fully hereinafter with reference to the accompanying drawings, in which preferred embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout. It will be understood that when an element is referred to as being "coupled" to another element, it can be directly coupled to the other element or intervening elements may also be present.

As will be appreciated by one of skill in the art, the present invention may be embodied as systems (apparatus) or methods. The present invention may take the form of an entirely hardware embodiment or an embodiment combining software and hardware aspects.

Accordingly, individual blocks and combinations of block in the drawings support combinations of means for performing the specified functions and combinations of steps for performing the specified functions. Each of the blocks of the drawings may be embodied in many different ways, as is well known to those of skill in the art.

Referring now to Figure 2, power IQ modulation systems and methods according to the present invention will now be described. As shown in Figure 2, power modulation systems and methods **200** modulate and amplify in-phase I and quadrature-phase Q input signals, in respective I and Q paths. Elements in the Q path are designated by the reference character **a** and elements in the I path are designated by the reference character **b**. As shown in Figure 2, first and second power amplifiers **210a** and **210b**, respectively, are included. Each of the first and second power amplifiers **210a** and **210b** includes a respective signal input **212a, 212b**, supply input **214a, 214b** and power output **216a, 216b**.

A reference frequency source **220** generates first, second, third and fourth reference frequency signals **222a-222d**. The first and second reference frequency signals **222a** and **222b** are inverted relative to one another and the third and fourth reference frequency signals **222c** and **222d** are inverted relative to one another.

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Preferably, the first through fourth reference frequency signals **222a-222d** are 0°, 180°, 90° and 270° phase shifted reference frequency signals, respectively,

As shown in Figure 2, the reference frequency source **220** preferably includes a controlled oscillator such as a voltage controlled oscillator **224** that produces the first reference frequency signal **222a** A phase-locked loop may also be included. A first inverter **226** is responsive to the controlled oscillator **224** to produce the second reference frequency signal **222b**. A phase shifter **228** is responsive to the controlled oscillator **224** to produce the third reference frequency signal **222c**. A second inverter **232** is responsive to the phase shifter **228** to produce the fourth reference frequency signal **222d**. However, it will be understood by those having skill in the art that many other techniques may be used to generate a reference frequency or phase inverted reference frequency signals under control of a sign bit.

Continuing with the description of Figure 2, a switching system **240** selectively applies one of the first and second reference frequency signals **222a** or **222b** to the signal input **212a** of the first power amplifier **210a** as a function of the polarity of one of the **I** and **Q** input signals, for example the **Q** input signal. The switching system **240** also selectively applies one of the third and fourth reference frequency signals **222c** or **222d** to the signal input **212b** of the second power amplifier **210b** as a function of the polarity of the other of the **I** and **Q** input signals, for example, the **I** input signal. First and second drivers **242a, 242b**, respectively, may be inserted between the switching system **240** and the respective class-C amplifier **210a, 210b** to overdrive the class-C amplifier **210a, 210b**, if necessary, to achieve the desired gain or drive power level for amplifiers **210a, 210b**.

As shown in Figure 2, the switching system preferably comprises a first switch such as a first Single-Pole Double-Throw (SPDT) switch **244a** that is responsive to the one of the **I** and **Q** input signals being positive to couple the first reference frequency signal **222a** to the first power amplifier **210a**, and that is responsive to the one of the **I** and **Q** input signals being negative to couple the second reference frequency signal **222b** to the first power amplifier **210a**. A second switch such as a second SPDT switch **244b**, is responsive to the other of the **I** and **Q** input signals being positive to couple the third reference frequency signal **222c** to the second power amplifier **210b**, and that is responsive to the other of the **I** and **Q** input signals being negative to couple the fourth reference signal **222d** to the second power amplifier

210b. One skilled in the art will understand that a balanced modulator may be used instead of SPDT switches to selectively invert a reference signal.

As also shown in Figure 2, the switching system 240 also preferably comprises a first polarity detector 246a that is coupled between the one of the I and Q input signals and the first switch 244a, to detect whether the one of the I and Q input signals is positive or negative. A second polarity detector 246b is coupled between the other of the I and Q input signals and the second switch 244b, to detect whether the other of the I and Q input signals is positive or negative.

Still continuing with the description of Figure 2, a third amplifier 250a, preferably a class-D amplifier, is responsive to the one of the I and Q input signals, for example the Q input signal, to supply a first variable supply voltage to the supply input 214a of the first amplifier 210a. A fourth amplifier 250b is responsive to the other of the I and Q input signals, for example the I input signal, to supply a second variable supply voltage to the supply input 214b of the second amplifier 210b.

In order to generate the appropriate inputs for the third and fourth amplifiers 250a and 250b, respectively, a first analog-to-digital converter, preferably a delta-sigma analog-to-digital converter 260a, is coupled between the one of the I and Q input signals and the third amplifier 250a, such that the third amplifier is responsive to a digital representation to the one of the I and Q signals to supply a first variable supply voltage to the supply input 214a of the first amplifier 210a. A second analog-to-digital converter, preferably a second delta-sigma analog-to-digital converter 260b, is coupled between the other of the I and Q input signals and the fourth amplifier 250b, such that the fourth amplifier 250b is responsive to a digital representation of the other of the I and Q signals to supply a second variable supply voltage input 214b of the second amplifier 210b. As shown in Figure 2, low pass filters 262a, 262b, 264a and 264b may filter the Q and I inputs and the outputs of the third and fourth amplifiers 250a and 250b respectively. Often, I and Q signals are generated in digital form by a Digital Signal Processor (DSP). The DSP can include lowpass filters 262a and 262b in digital form. Delta-Sigma converters 260a and 260b can then convert the filtered digital sample streams from the DSP from a Pulse Coded Modulation (PCM) format to a Delta-Sigma representation by an entirely digital logic process and system.

Finally, a coupler 270 couples the power outputs 216a and 216b of the first and second power amplifiers 210a and 210b to a load 272 such as radiotelephone

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antenna. In one embodiment, the coupler **270** includes a matching network that couples the first and second power amplifiers to the load **272** while preferably isolating the first and second power amplifiers **210a** and **210b** from one another.

Operation of power modulation systems and methods of Figure 2 will now be described. The frequency of the controlled oscillator **224** is preferably set to the transmitted carrier frequency. The 90° phase shifter **228** preferably creates an identical signal but with a phase shift of 90° from the original signal. The original signal and the 90° shifted signal are then sent to inverters **226** and **232**, which are amplifiers with a gain of –1. Thus, four reference frequency signals **222a-222d** are present. They preferably represent +sin and –sin, and +cos and –cos of the controlled oscillator **224**.

The two switches **244a** and **244b** are controlled to select a polarity of the sin for one channel and a polarity of the cos for the other channel. These signals proceed independently to the driver amplifier stages **242a** and **242b** and the power amplifier outputs stages **210a** and **210b**.

The control of the polarity of the sin or cos signals preferably coincides with the amplitude of the **I** or **Q** channel becoming zero. This can reduce introduction of polarity change induced noise into the output signal spectrum.

The two power amplifier output stages are preferably coupled with series blocking capacitors in the matching network **270** so that the supply voltages, preferably corresponding to drain voltages of the class-C amplifiers, can be controlled independent of each other. Preferably, the distance from the class-C amplifiers **210a** and **210b** to the matching network **270** is short relative to the wavelength of the carrier frequency.

The class-C amplifier supply voltages **214a** and **214b** preferably are created in an efficient manner by class-D amplifiers **250a** and **250b**, using low pass filters **246a** and **246b** to remove the switching noise. The input signals to the class-D amplifiers **250a** and **250b** are created by a delta-sigma process so that the noise in the bandwidth of the low pass filters **246a** and **246b** can be reduced. Accordingly, using the appropriate **I** and **Q** signals, it is possible to create any desired trajectory in the vector of the phase plane. The Class D amplifiers are preferably capable both of sourcing and sinking current so that current can even flow from the amplifiers **210a** and **210b** back to the supply during periods of a modulation cycle.

The power amplifiers **210a** and **210b** preferably are saturated class-C amplifiers rather than linear power amplifiers. Higher efficiency may therefore be obtained. Out-of-band noise can be reduced, which can eliminate the need for additional SAW filters in the chain. Finally, a large modulation bandwidth can be supported. This bandwidth may be limited only by the filter bandwidth of the low pass filters **264a** and **264b** that follow the class-D amplifier stages **250a** and **250b**, respectively.

Figure 3 is a block diagram of a second embodiment of power IQ modulation systems and methods according to the invention. Power modulation systems and methods **200'** of Figure 3 are similar to those of Figure 2, except that a respective quarter wavelength transmission line **310a** and **310b** of appropriate impedance is included in each branch of the final output stage between the power output **216a** and **216b** of the class-C amplifiers **210a** and **210b** and the matching network **270**, as disclosed in the above-incorporated applications.

Alternatively, in a third embodiment **200''** shown in Figure 4, a pair of isolators **410a** and **410b** may be included between the power outputs **216a** and **216b** and the matching network **270**. Although this arrangement may not provide high efficiency, it may offer a simplified combination and the possibility of improved linearity for applications where that is desired. As an example, matching network **270** may be two separate matching networks, each connected to an isolator **410** that increases the impedance from 50 ohms at the isolator to 100 ohms at the point where the two matching networks are joined and attached to the feedline to antenna **272**.

Figure 5 illustrates yet another embodiment **200'''** wherein the matching network **270** is replaced by a pair of voltage-to-current (VI) converters and matching networks **570a** and **570b**.

Each of the embodiments of Figures 3-5 may have various advantages and disadvantages. For example, the embodiment of Figure 3 uses quarter wavelength transmission lines **310a** and **310b** to convert the predominantly voltage source of the power amplifier stages **210a** and **210b** to currents. The currents can then be added in parallel and supplied to the load through the matching network **270**.

The embodiment of Figure 4 uses a pair of isolators **410a** and **410b** to combine the outputs from the two power amplifier output stages **210a** and **210b**. The isolators may reduce interaction between the two power amplifier stages **210a** and **210b** at the expense of overall efficiency. Finally, the embodiment of Figure 5 uses

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the matching network **570a** and **570b** to convert the voltage output of the class-C amplifiers **210a** and **210b** to current for addition in the load.

Class-C amplifiers **210a, 210b** can have a nonlinear relationship between supply voltage and output level, resulting in distortion. Such amplifiers can also suffer from Amplitude Modulation to Phase Modulation (AM-to-PM) conversion, whereby modulation of the amplitude produces undesired modulation of the phase. The invention can also include methods and systems to compensate for such signal distortion.

Such precompensation can be either feedforward precompensation, where I and Q signals are precompensated for the known distortion that the amplifiers will introduce, or feedback precompensation where the phase or amplitude of the output signal is sensed, compared to desired values to obtain error quantities, the error quantities then being used to generate corrected I, Q values that will result in the desired output signal being produced more accurately. Feedback systems can also be either real-time feedback systems, or "off-line" or "learning" systems which gradually adjust the way in which I, Q values are precompensated so as to produce the desired output signal more accurately.

In general, output signal amplitude may be measured using a power detector, but output phase may be more difficult to measure, as phase generally is measured relative to a phase reference signal. Therefore, although a feedback technique of controlling amplitude linearity may be quite practical, a feedforward technique of compensating for AM-to-PM conversion may be more practical.

A preferred technique of compensating distortion comprises use of a digital signal processor to generate compensated I and Q signals. For example, a technique of precompensating conventional amplifiers as well as AM-to-PM conversion that depends on the total output signal amplitude, can comprise using the digital signal processor to compute the desired total amplitude of the output signal from the square root of $I^2 + Q^2$.

The desired amplitude is then applied as an address to a prestored look-up table to obtain an amplitude compensating value that is used to scale both the I and Q values to obtain amplitude-compensated I and Q values which, when then used for modulation, can result in the correct, desired output signal amplitude being produced.

Either the original desired amplitude or the compensated amplitude may then be applied to a prestored phase compensating table to obtain a phase compensating value that compensates for AM-to-PM conversion. The phase compensating value is then used in complex multiplication with the amplitude-compensated I and Q values to obtain phase and amplitude compensated I and Q values that, when used for modulation, can result in the correct, desired signal amplitude being produced.

The number of multiplications generally needed for precompensating for AM-to-PM conversion and for amplitude nonlinearity is 6, but this may be reduced to 4 by the following technique:

Denote the desired amplitude by $A(t)=(I(t)^2 + Q(t)^2)^{1/2}$. Then if the amplifier produces an amplitude distortion function F(A) and a phase rotation equivalent to multiplication by the complex number $[\cos(\phi(A)), \sin(\phi(A))]$, then the original I,Q values should be corrected when modified by the following equation:

$$\begin{bmatrix} I' \\ Q' \end{bmatrix} = F^{-1}(A)/A \begin{bmatrix} \cos(\phi) & \sin(\phi) \\ -\sin(\phi) & \cos(\phi) \end{bmatrix} \begin{bmatrix} I \\ Q \end{bmatrix} .$$

Therefore,

$$I' = F^{-1}(A)/A \cos(\phi)\, I + F^{-1}(A)/A \sin(\phi)\, Q$$

$$Q' = F^{-1}(A)/A \cos(\phi)\, Q - F^{-1}(A)/A \sin(\phi)\, I$$

Since $F^{-1}(A)/A \cos(\phi)$ and $F^{-1}(A)/A \sin(\phi)$ are purely functions of the amplitude A, they can be precomputed and stored in a look-up table as F1(A) and F2(A), and then used as above. Thus, only four multiplications may be used to correct both phase and amplitude distortion.

In the inventive amplifiers described herein, each amplifier amplifies only the I part or the Q part. Therefore it may be expected that amplitude distortion in the I-amplifier would be dominantly dependent on only the I value, while amplitude distortion in the Q-amplifier would be dominantly dependent on the Q value. Likewise, AM-to-PM conversion in the I-amplifier would change the signal phase away from zero (the cosine wave phase) by a phase error amount depending dominantly on the I-value, while AM-to-PM conversion in the Q amplifier would change its signal phase away from 90 degrees (the sine wave phase) by a phase error

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amount depending dominantly on the Q value. Thus a different precompensation structure may be used to compensate for two different values of AM-to-PM conversion and amplitude distortion, one dependent only on the I-value and the other dependent only on the Q value.

If the AM-to-PM conversion of the I amplifier is described by $\phi(I)$ then the magnitude of the I value will be reduced to $I\cos(\phi(I))$ and an additive error component $I\sin(\phi(I))$ will be added to the Q value. Likewise, describing AM-to-PM conversion of the Q amplifier by $\phi(Q)$, the magnitude of Q will be reduced to $Q\cos(\phi(Q))$, while an additive error $Q\sin(\phi(Q))$ will be subtracted from the I component. If in addition there is an amplitude distortion from I to F(I) and an amplitude distortion from Q to F(Q) that shall be corrected by applying the inverse of the function F, then the total precompensation of the amplitude of I needed is described by the function:

$$(F^{-1}(I))/(\cos(\phi(I)))$$

and the total precompensation of the amplitude Q needed is described by the function:

$$(F^{-1}(Q))/(\cos(\phi(Q))).$$

If the amplifiers are equal, then these functions are the same function with argument I in one case and Q in the other. The entire function may be precomputed and stored. Whether the error component additive to Q produced by the I amplifier is caused by the desired value of I or the precompensated value of I using the above function, it is still dependent only on the value of I and so may also be precomputed and stored in a look-up table for $I\cos(\phi(I))$, and likewise for the error additive to the I value produced in the Q channel.

A block diagram of precompensation according to the invention is shown in Figure 6. The desired I value is applied to a look-up table **600a** to obtain a compensated I value F1(I), also referred to as a first amplitude distortion compensating value **610a**, and an AM-to-PM compensating value F2(I), also referred to as a first phase compensating value **620a**. Likewise the desired Q value is applied to a look-up table **600b**, which can be the same look-up table if the amplifiers **210a, 210b** and their associated high-level class-D modulators **250a, 250b** are identical. If the amplifiers are differently calibrated, then the two look-up tables denoted by **600a, 600b** in Figure 6 can be different subtables of a single lookup table system **600**.

The Q value addresses the lookup table **600b**, to produce an amplitude-precompensated Q value F1(Q), also referred to as a second amplitude distortion compensating value **610b**, and an AM-to-PM compensating value F2(Q), also referred to as a second phase compensating value **620b**. The value F2(Q) is added to the value F1(I) in adder **630a** while the value F2(I) is subtracted from the value F1(Q) in subtractor **630b** of a summer **630**. Summer **630** produces precompensated or predistorted I and Q values which, when applied to modulate respective amplifiers, will result in an output after combining the amplifier outputs that more accurately follows the desired I and Q values. The compensated I and Q values may be used to modulate respective amplifiers by applying the modulus (magnitude) of the compensated I value to the high-level, class-D I-modulator **260b, 250b, 264b** while applying the sign of the compensated I value to select either inverted or not-inverted phase of cosine wave reference signal from generator **224**. Likewise, the modulus (magnitude) of the compensated Q value is applied to the Q-modulator **260a, 250a, 264a** while the sign of the compensated Q value selects either inverted or not-inverted sine wave drive from reference **224** shifted in phase by 90 degrees **228**.

The above techniques which can compensate either for total-amplitude dependent distortion or distortion dependent on the I and Q components separately may be used together, if distortion of both types exists. The two techniques may be applied in any order, by ensuring that the look-up tables precomputed for the first-applied technique account for distortion already compensated by the second-applied technique.

Other methods of improving linearity include Cartesian Feedback, as for example described in U.S. Patent no. 5,483,681 to Bergsten et al, which is hereby incorporated by reference herein.

Accordingly, high efficiency power IQ modulation systems and methods may be provided to thereby allow a reduction in the cost, size and/or power consumption of a cellular radiotelephone or other transmitter.

In the drawings and specification, there have been disclosed typical preferred embodiments of the invention and, although specific terms are employed, they are used in a generic and descriptive sense only and not for purposes of limitation, the scope of the invention being set forth in the following claims.

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What is Claimed is:

1. A power modulation system that modulates and amplifies in-phase (I) and quadrature-phase (Q) input signals, the power modulation system comprising:

first and second power amplifiers, each including a signal input, a supply input and a power output;

a source of first, second, third and fourth reference frequency signals, the first and second reference frequency signals being inverted relative to one another and the third and fourth reference frequency signals being inverted relative to one another;

a switching system that selectively applies one of the first and second reference frequency signals to the signal input of the first power amplifier as a function of the polarity of one of the I and Q input signals, and that selectively applies one of the third and fourth reference frequency signals to the signal input of the second power amplifier as a function of the polarity of the other of the I and Q input signals;

a third amplifier that is responsive to the one of the I and Q input signals to supply a first variable supply voltage to the supply input of the first power amplifier;

a fourth amplifier that is responsive to the other of the I and Q input signals to supply a second variable supply voltage to the supply input of the second power amplifier; and

a coupler that couples the power outputs of the first and second power amplifiers to a load.

2. A power modulation system according to Claim 1 wherein the first and second power amplifiers comprise class-C power amplifiers and wherein the third and fourth amplifiers comprise class-D power amplifiers.

3. A power modulation system according to Claim 1 wherein the first, second, third and fourth reference frequency signals are 0°, 180°, 90° and 270° phase shifted reference frequency signals, respectively.

4. A power modulation system according to Claim 1 wherein the source of first, second, third and fourth reference frequency signals comprises:

a controlled oscillator that produces the first reference frequency signal;

a first inverter that is responsive to the controlled oscillator to produce the second reference frequency signal;

a phase shifter that is responsive to the controlled oscillator to produce the third reference frequency signal; and

a second inverter that is responsive to the phase shifter to produce the fourth reference frequency signal.

5. A power modulation system according to Claim 1 wherein the switching system comprises:

a first switch that is responsive to the one of the I and Q input signals being positive to couple the first reference frequency signal to the first power amplifier, and that is responsive to the one of the I and Q input signals being negative to couple the second reference frequency signal to the first power amplifier; and

a second switch that is responsive to the other of the I and Q input signals being positive to couple the third reference frequency signal to the second power amplifier, and that is responsive to the other of the I and Q input signals being negative to couple the fourth reference frequency signal to the second power amplifier.

6. A power modulation system according to Claim 5 wherein the switching system further comprises:

a first polarity detector that is coupled between the one of the I and Q input signals and the first switch, to detect whether the one of the I and Q input signals is positive or negative; and

a second polarity detector that is coupled between the other of the I and Q input signals and the second switch, to detect whether the other of the I and Q input signals is positive or negative.

7. A power modulation system according to Claim 1 further comprising:

a first analog-to-digital converter that is coupled between the one of the I and Q input signals and the third amplifier, such that the third amplifier is responsive to a digital representation of the one of the I and Q signals to supply a first variable supply voltage to the supply input of the first amplifier; and

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a second analog-to-digital converter that is coupled between the other of the I and Q input signals and the fourth amplifier, such that the fourth amplifier is responsive to a digital representation of the other of the I and Q signals to supply a second variable supply voltage to the supply input of the second amplifier.

8. A power modulation system according to Claim 7 wherein the first analog-to-digital converter comprises a first delta-sigma analog-to-digital converter and wherein the second analog-to-digital converter comprises a second delta-sigma analog-to-digital converter.

9. A power modulation system according to Claim 1 wherein the coupler comprises a matching network that couples the first and second power amplifiers to a load.

10. A power modulation system according to Claim 9 wherein the coupler further comprises a first quarter wavelength transmission line that couples the first power amplifier to the matching network and a second quarter wavelength transmission line that couples the second power amplifier to the matching network.

11. A power modulation system according to Claim 9 wherein the coupler further comprises a first isolator that couples the first power amplifier to the matching network and a second isolator that couples the second power amplifier to the matching network.

12. A power modulation system according to Claim 1 wherein the first and second power amplifiers produce nonlinear distortion, the power modulation system further comprising:

a compensation system that is responsive to the I and Q input signals, to generate predistorted I and Q signals and to apply the predistorted I and Q signals to at least one of the switching system and to the third and fourth amplifiers, to thereby compensate for the nonlinear distortion.

13. A power modulation system according to Claim 12 wherein the compensation system comprises:

a look-up table that is responsive to the I input signal to produce a first amplitude distortion compensating value and a first phase compensating value, and that is responsive to the Q input signal to produce a second amplitude distortion compensating value and a second phase compensating value; and

a summer that adds the first amplitude distortion compensating value and the second phase compensating value to produce the predistorted I signal, and that subtracts the first phase compensating value from the second amplitude distortion compensating value to produce the predistorted Q signal.

14. A power modulation system according to Claim 13:

wherein the look-up table is a pair of look-up subtables, a respective one of which is responsive to a respective one of the I input signal and the Q input signal; and

wherein the summer comprises an adder that adds the first amplitude distortion compensating value and the second phase compensating value to produce the predistorted I signal, and a subtractor that subtracts the first phase compensating value from the second amplitude distortion compensating value to produce the predistorted Q signal.

15. A power modulation system according to Claim 1 wherein the I and Q input signals are I and Q radiotelephone communication signals and wherein the load is a radiotelephone antenna.

16. A power modulation system that modulates and amplifies in-phase (I) and quadrature-phase (Q) input signals, the power modulation system comprising:

first and second means for power amplifying a signal input to produce a power output in response to a supply input;

means for providing first, second, third and fourth reference frequency signals, the first and second reference frequency signals being inverted relative to one another and the third and fourth reference frequency signals being inverted relative to one another;

means for selectively applying one of the first and second reference frequency signals to the signal input of the first means for power amplifying as a function of the polarity of one of the I and Q input signals, and for selectively applying one of the

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third and fourth reference frequency signals to the signal input of the second means for power amplifying as a function of the polarity of the other of the I and Q input signals;

means for supplying a first variable supply voltage to the supply input of the first means for power amplifying in response to the one of the I and Q input signals;

means for supplying a second variable supply voltage to the supply input of the second means for power amplifying in response to the other of the I and Q input signals; and

means for coupling the power outputs of the first and second means for power amplifying to a load.

17. A power modulation system according to Claim 16 wherein the first and second means for power amplifying comprise class-C power amplifiers and wherein the means for supplying comprise class-D power amplifiers.

18. A power modulation system according to Claim 16 wherein the first, second, third and fourth reference frequency signals are 0°, 180°, 90° and 270° phase shifted reference frequency signals, respectively.

19. A power modulation system according to Claim 16 wherein the means for providing first, second, third and fourth reference frequency signals comprises:

means for producing the first reference frequency signal;

means for inverting the first reference frequency signal to produce the second reference frequency signal;

means for phase shifting the first reference frequency signal to produce the third reference frequency signal; and

means for inverting the third reference frequency signal to produce the fourth reference frequency signal.

20. A power modulation system according to Claim 16 wherein the means for selectively applying comprises:

first means for coupling the first reference frequency signal to the first power amplifying means in response to the one of the I and Q input signals being positive and for coupling the second reference frequency signal to the first power amplifying means in response to the one of the I and Q input signals being negative; and

second means for coupling the third reference frequency signal to the second power amplifying means in response to the other of the I and Q input signals being positive and for coupling the fourth reference frequency signal to the second power amplifying means in response to the other of the I and Q input signals being negative.

21. A power modulation system according to Claim 20 wherein the means for selectively applying further comprises:

first means for detecting whether the one of the I and Q input signals is positive or negative, the first means for coupling being responsive to the first means for detecting; and

second means for detecting whether the other of the I and Q input signals is positive or negative, the second means for coupling being responsive to the second means for detecting.

22. A power modulation system according to Claim 16 further comprising:

first means for converting the one of the I and Q input signals to digital, such that the means for supplying a first variable supply voltage is responsive to a digital representation of the one of the I and Q signals; and

second means for converting the other of the I and Q input signals to digital, such that the means for supplying a second variable supply voltage is responsive to a digital representation of the other of the I and Q signals.

23. A power modulation system according to Claim 22 wherein the first means for converting comprises a first delta-sigma analog-to-digital converter and wherein the second means for converting comprises a second delta-sigma analog-to-digital converter.

24. A power modulation system according to Claim 16 wherein the means for coupling comprises means for matching the first and second means for power amplifying to a load.

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25. A power modulation system according to Claim 24 wherein the means for coupling further comprises a first quarter wavelength transmission line that couples the first means for power amplifying to the means for matching and a second quarter wavelength transmission line that couples the second means for power amplifying to the means for matching.

26. A power modulation system according to Claim 24 wherein the means for coupling further comprises means for isolating the first means for power amplifying and the second means for power amplifying from one another.

27. A power modulation system according to Claim 24 wherein the means for matching comprises means for converting voltage to current.

28. A power modulation system according to Claim 16 wherein the first and second means for power amplifying produce nonlinear distortion, the power modulation system further comprising:

means for generating predistorted I and Q signals from the I and Q input signals and for applying the predistorted I and Q signals to at least one of the means for selectively applying and the means for supplying, to thereby compensate for the nonlinear distortion.

29. A power modulation system according to Claim 28 wherein the means for generating comprises:

means for producing a first amplitude distortion compensating value and a first phase compensating value in response to the I input signal and for producing a second amplitude distortion compensating value and a second phase compensating value in response to the Q input signal; and

means for adding the first amplitude distortion compensating value and the second phase compensating value to produce the predistorted I signal, and for subtracting the first phase compensating value from the second amplitude distortion compensating value to produce the predistorted Q signal.

30. A power modulation system according to Claim 16 wherein the I and Q input signals are I and Q radiotelephone communication signals and wherein the load is a radiotelephone antenna.

31. A method for modulating and amplifying in-phase (I) and quadrature-phase (Q) input signals, using first and second means for power amplifying a signal input to produce a power output in response to a supply input, the method comprising the steps of:

providing first, second, third and fourth reference frequency signals, the first and second reference frequency signals being inverted relative to one another and the third and fourth reference frequency signals being inverted relative to one another;

selectively applying one of the first and second reference frequency signals to the signal input of the first means for power amplifying, as a function of the polarity of one of the I and Q input signals;

selectively applying one of the third and fourth reference frequency signals to the signal input of the second means for power amplifying, as a function of the polarity of the other of the I and Q input signals;

supplying a first variable supply voltage to the supply input of the first means for power amplifying in response to the one of the I and Q input signals;

supplying a second variable supply voltage to the supply input of the second means for power amplifying in response to the other of the I and Q input signals; and

coupling the power outputs of the first and second means for power amplifying to a load.

32. A method according to Claim 31 wherein the first and second means for power amplifying comprise class-C power amplifiers and wherein the supplying steps use class-D power amplifiers.

33. A method according to Claim 31 wherein the first, second, third and fourth reference frequency signals are 0°, 180°, 90° and 270° phase shifted reference frequency signals, respectively.

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34. A method according to Claim 31 wherein the step of providing first, second, third and fourth reference frequency signals comprises the steps of:

producing the first reference frequency signal;

inverting the first reference frequency signal to produce the second reference frequency signal;

phase shifting the first reference frequency signal to produce the third reference frequency signal; and

inverting the third reference frequency signal to produce the fourth reference frequency signal.

35. A method according to Claim 31 wherein the steps of selectively applying comprise the steps of:

coupling the first reference frequency signal to the first power amplifying means in response to the one of the I and Q input signals being positive;

coupling the second reference frequency signal to the first power amplifying means in response to the one of the I and Q input signals being negative;

coupling the third reference frequency signal to the second power amplifying means in response to the other of the I and Q input signals being positive; and

coupling the fourth reference frequency signal to the second power amplifying means in response to the other of the I and Q input signals being negative.

36. A method according to Claim 35 wherein the steps of selectively applying further comprise the steps of:

detecting whether the one of the I and Q input signals is positive or negative; and

detecting whether the other of the I and Q input signals is positive or negative.

37. A method according to Claim 31 further comprising the steps of:

converting the one of the I and Q input signals to digital, such that the step of supplying a first variable supply voltage is responsive to a digital representation of the one of the I and Q signals; and

converting the other of the I and Q input signals to digital, such that the step of supplying a second variable supply voltage is responsive to a digital representation of the other of the I and Q signals.

38. A method according to Claim 37 wherein the steps of converting comprise the steps of delta-sigma converting.

39. A method according to Claim 31 wherein the step of coupling comprises the step of matching the first and second means for power amplifying to a load.

40. A method according to Claim 39 wherein the step of coupling comprises the step of quarter wavelength transmission line matching the first means for power amplifying and the second means for power amplifying.

41. A method according to Claim 39 wherein the step of coupling comprises the step of isolating the first means for power amplifying and the second means for power amplifying from one another.

42. A method according to Claim 39 wherein the step of matching further comprises the step of converting voltage to current.

43. A method according to Claim 31 wherein the first and second means for power amplifying produce nonlinear distortion, the power modulation method further comprising the step of:

generating predistorted I and Q signals from the I and Q input signals, at least one of the selectively applying steps and the supplying steps being responsive to the predistorted I and Q signals, to thereby compensate for the nonlinear distortion.

44. A method according to Claim 43 wherein the generating step comprises the steps of:

producing a first amplitude distortion compensating value and a first phase compensating value in response to the I input signal;

producing a second amplitude distortion compensating value and a second phase compensating value in response to the Q input signal;

adding the first amplitude distortion compensating value and the second phase compensating value to produce the predistorted I signal; and

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subtracting the first phase compensating value from the second amplitude distortion compensating value to produce the predistorted Q signal.

45. A power modulation method according to Claim 31 wherein the I and Q input signals are I and Q radiotelephone communication signals and wherein the load is a radiotelephone antenna.

46. A system that amplifies in-phase (I) and quadrature-phase (Q) input signals, the system comprising:

first and second power amplifiers that produce nonlinear distortion; and

a compensation system that is responsive to the I and Q input signals, to generate predistorted I and Q signals, to apply the predistorted I signal to the first power amplifier and to apply the predistorted Q signal to the second power amplifier, to thereby compensate for the nonlinear distortion.

47. A system according to Claim 46 wherein the compensation system comprises:

a look-up table that is responsive to the I input signal to produce a first amplitude distortion compensating value and a first phase compensating value, and that is responsive to the Q input signal to produce a second amplitude distortion compensating value and a second phase compensating value; and

a summer that adds the first amplitude distortion compensating value and the second phase compensating value to produce the predistorted I signal, and that subtracts the first phase compensating value from the second amplitude distortion compensating value to produce the predistorted Q signal.

48. A system according to Claim 47:

wherein the look-up table is a pair of look-up subtables, a respective one of which is responsive to a respective one of the I input signal and the Q input signal; and

wherein the summer comprises an adder that adds the first amplitude distortion compensating value and the second phase compensating value to produce the predistorted I signal, and a subtractor that subtracts the first phase compensating

value from the second amplitude distortion compensating value to produce the predistorted Q signal.

49. A system that amplifies in-phase (I) and quadrature-phase (Q) input signals, the system comprising:

first and second means for power amplifying that produce nonlinear distortion; and

means for generating predistorted I and Q signals from the I and Q input signals, for applying the predistorted I signal to the first means for power amplifying and for applying the predistorted Q signal to the second means for power amplifying, to thereby compensate for the nonlinear distortion.

50. A power modulation system according to Claim 49 wherein the means for generating comprises:

means for producing a first amplitude distortion compensating value and a first phase compensating value in response to the I input signal and for producing a second amplitude distortion compensating value and a second phase compensating value in response to the Q input signal; and

means for adding the first amplitude distortion compensating value and the second phase compensating value to produce the predistorted I signal, and for subtracting the first phase compensating value from the second amplitude distortion compensating value to produce the predistorted Q signal.

51. A method for amplifying in-phase (I) and quadrature-phase (Q) input signals, the method comprising the steps of:

generating predistorted I and Q signals from the I and Q input signals;

applying the predistorted I signal to first power amplifying means; and

applying the predistorted Q signal to second power amplifying means, to thereby compensate for nonlinear distortion in the first and second power amplifying means.

52. A method according to Claim 51 wherein the generating step comprises the steps of:

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producing a first amplitude distortion compensating value and a first phase compensating value in response to the I input signal;

producing a second amplitude distortion compensating value and a second phase compensating value in response to the Q input signal;

adding the first amplitude distortion compensating value and the second phase compensating value to produce the predistorted I signal; and

subtracting the first phase compensating value from the second amplitude distortion compensating value to produce the predistorted Q signal.

FIG. 1
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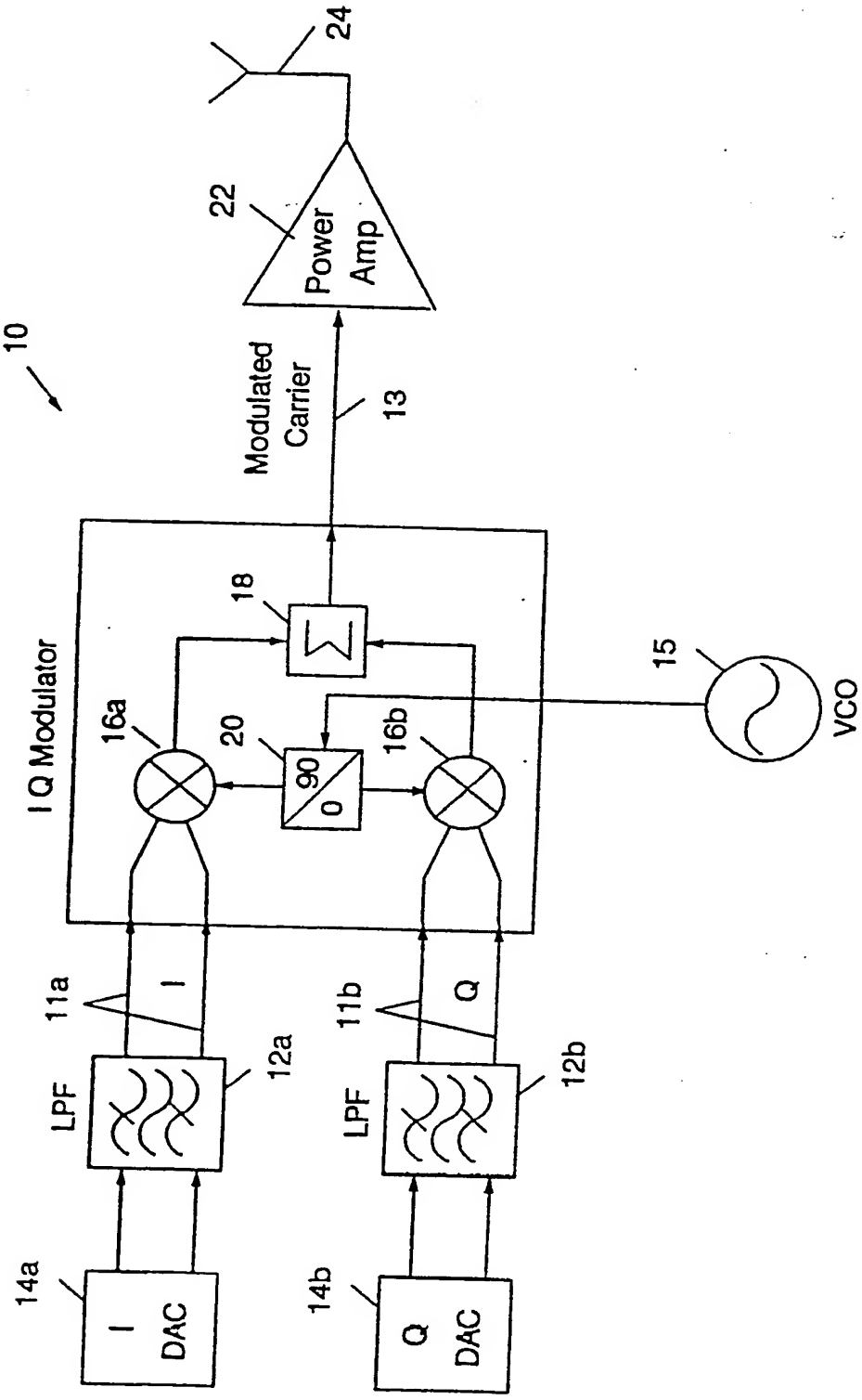

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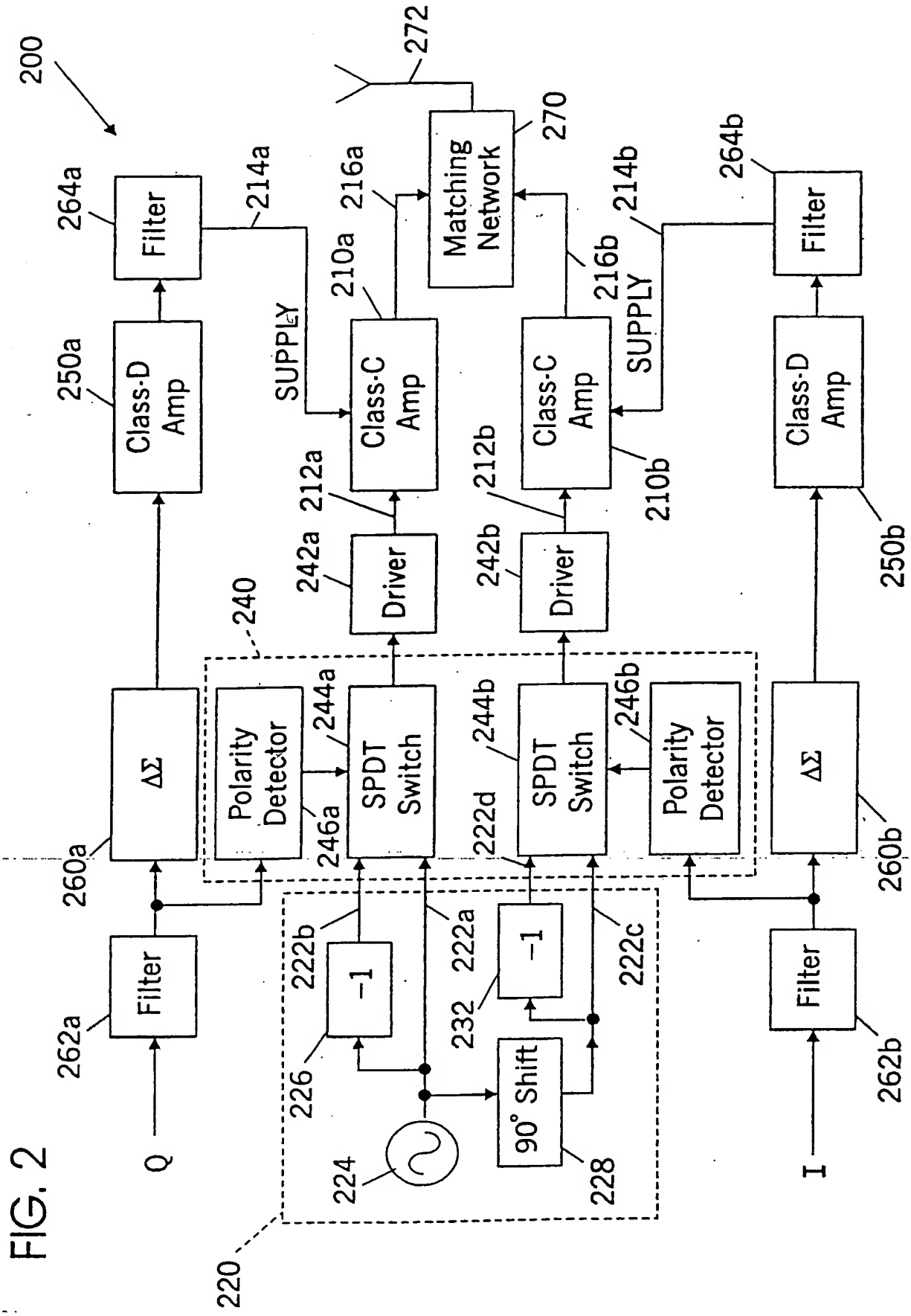
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264b
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Filter
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216b
SUPPLY
Class-C Amp
Class-D Amp
250b
212a
212b
210b
242a
Driver
242b
Driver
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ΔΣ
Polarity Detector
244a
SPDT Switch
244b
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ΔΣ
260a
246a
222d
260b
Filter
Filter
262a
262b
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Q
I
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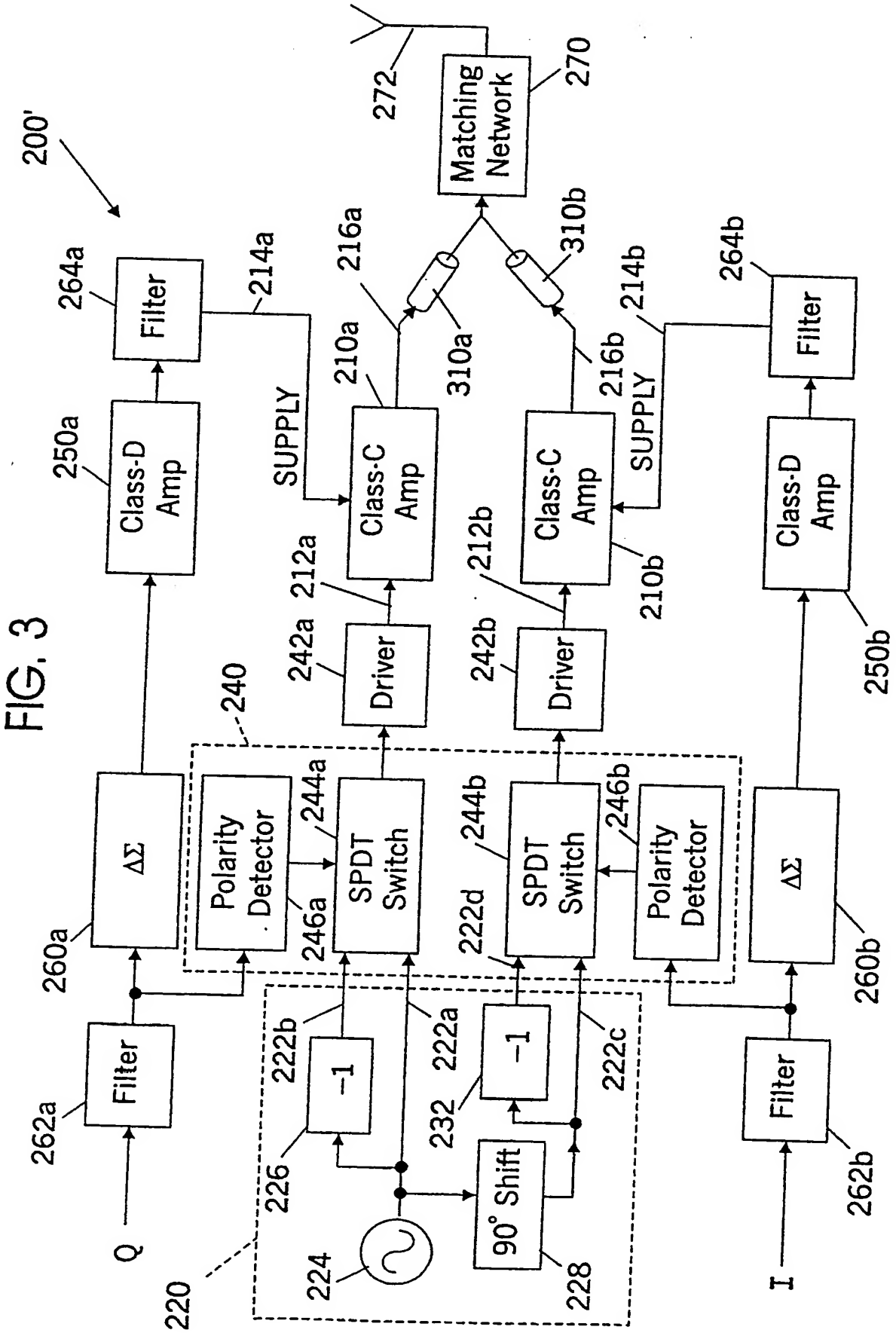
FIG. 2

FIG. 3



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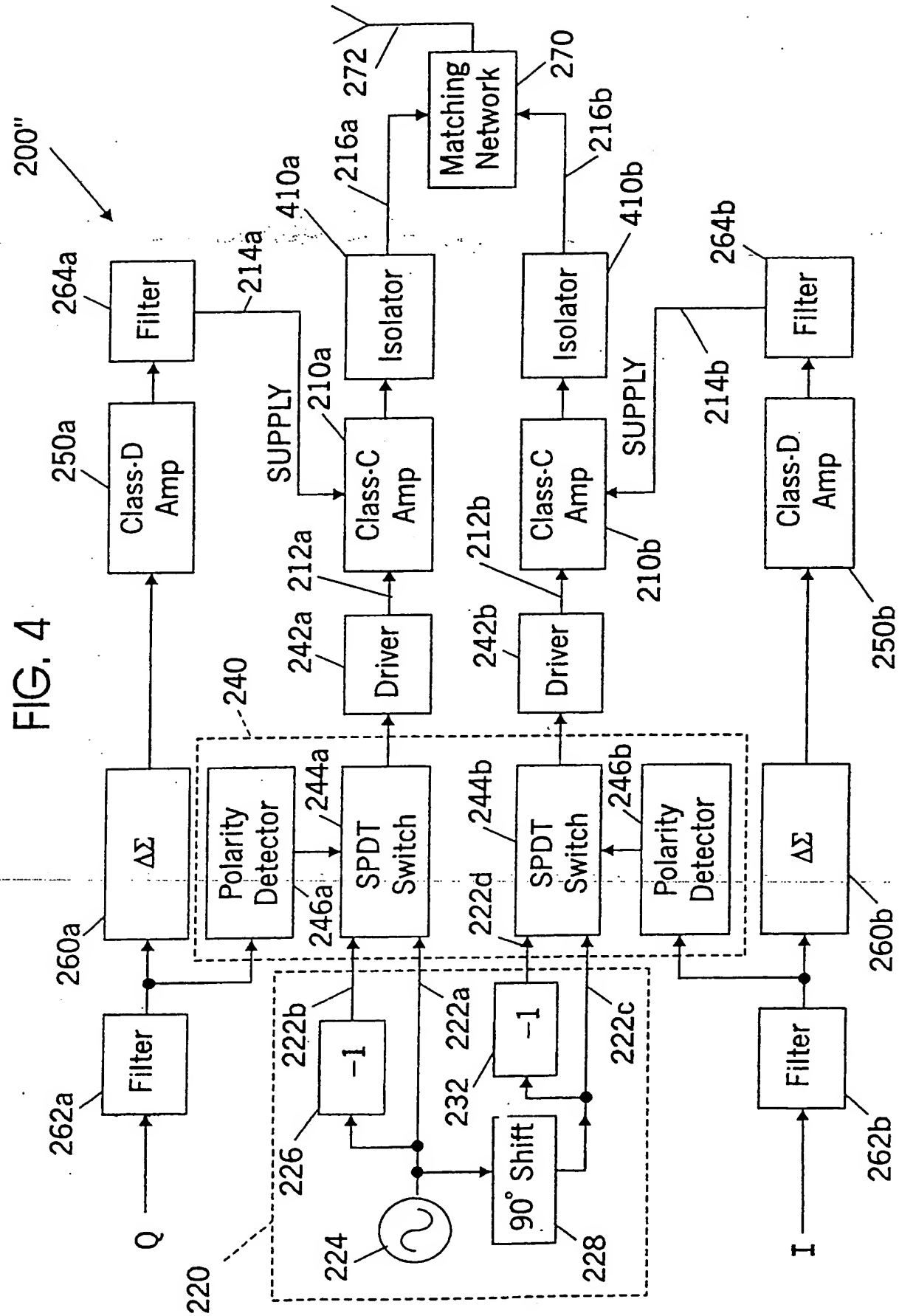
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Class-C Amp
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212b
Driver
Driver
242a
242b
250a
250b
Class-D Amp
Class-D Amp
240
Polarity Detector
Polarity Detector
244a
244b
246a
246b
SPDT Switch
SPDT Switch
222d
ΔΣ
ΔΣ
260a
260b
Filter
Filter
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222a
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226
224
90° Shift
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220

FIG. 4

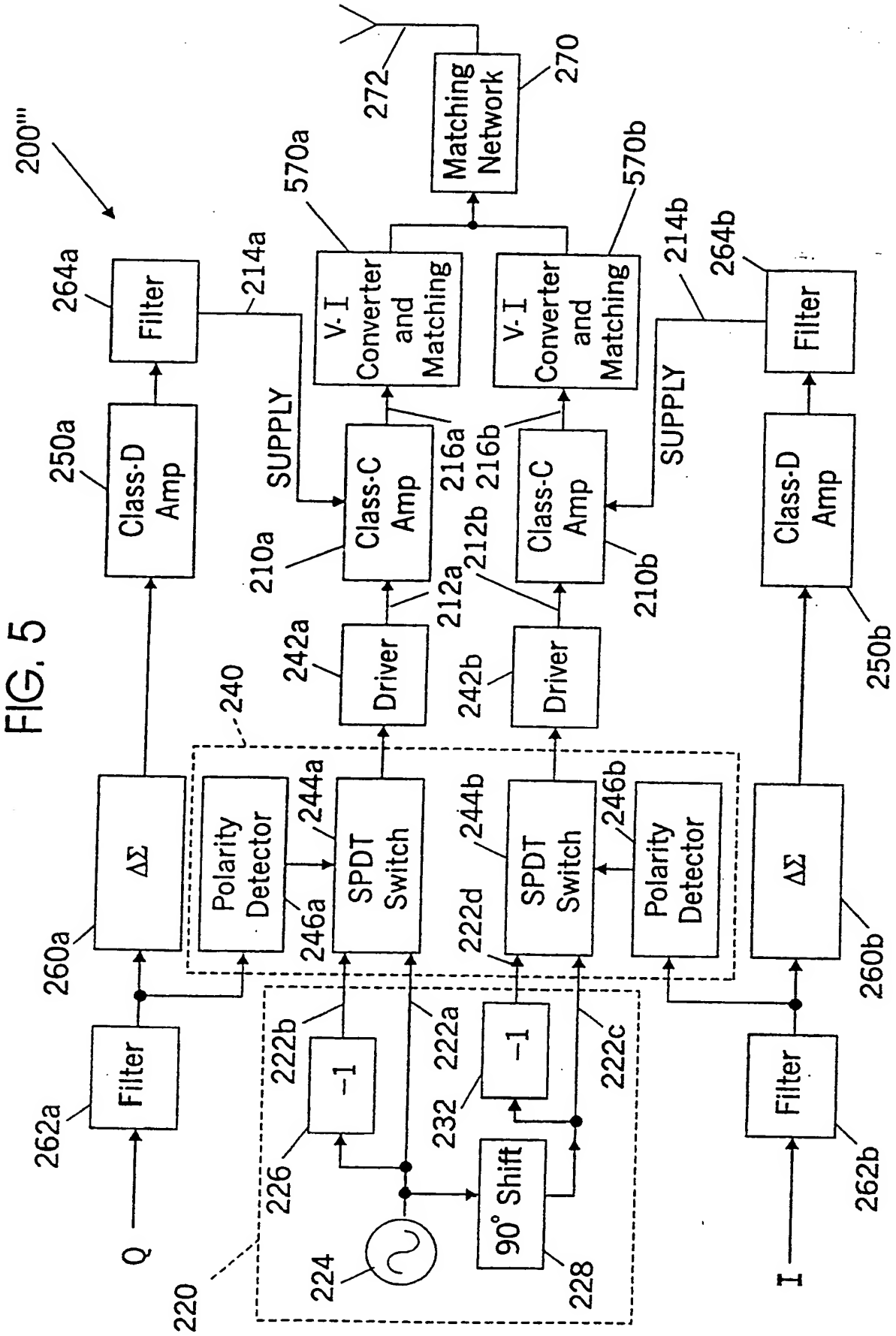

FIG. 5

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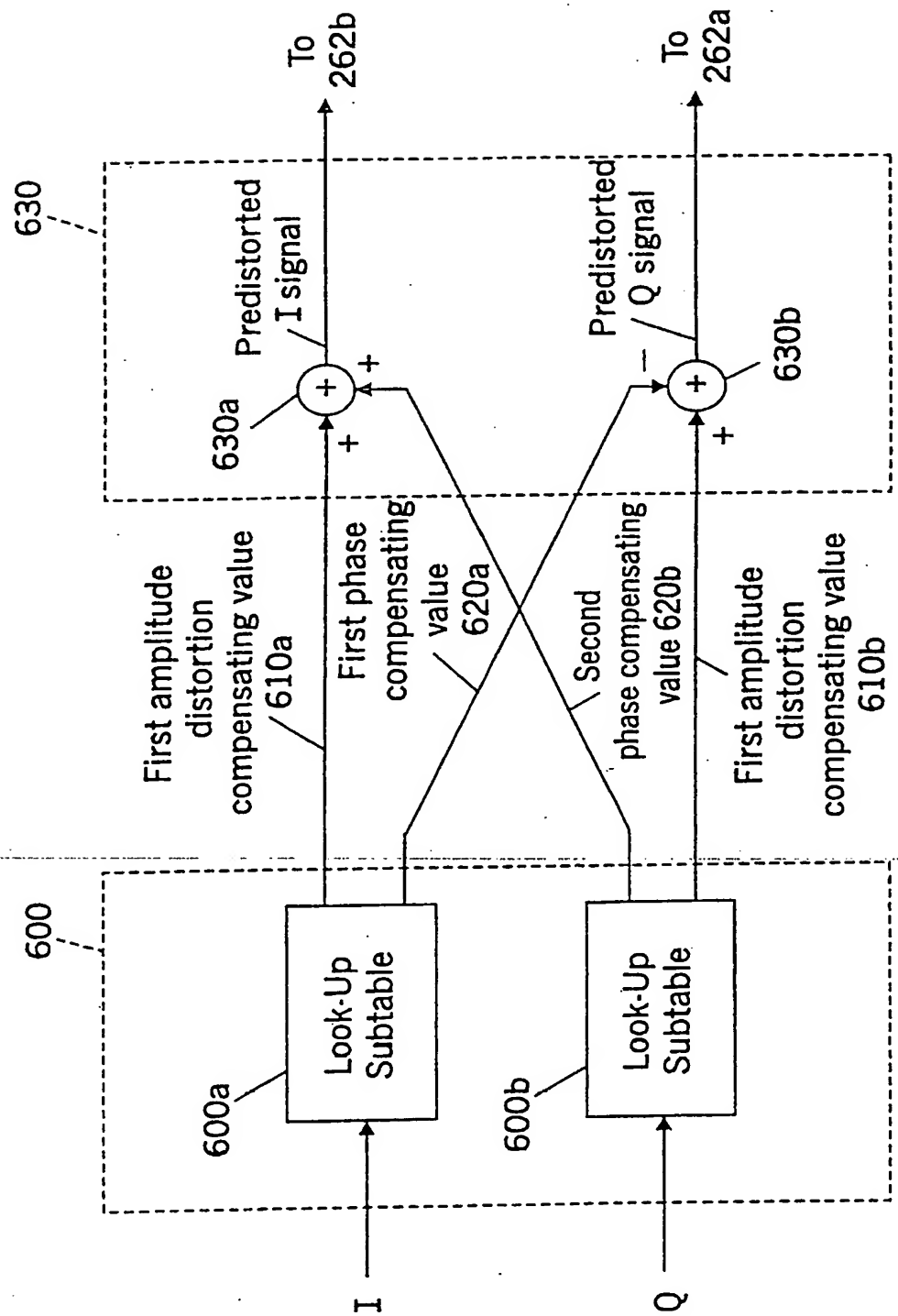
FIG. 6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630
To 262b
To 262a
Predistorted I signal
Predistorted Q signal
630a
630b
+
+
+
+
−
First amplitude distortion compensating value 610a
First phase compensating value 620a
Second phase compensating value 620b
First amplitude distortion compensating value 610b
600a
600b
Look-Up Subtable
Look-Up Subtable
I
Q

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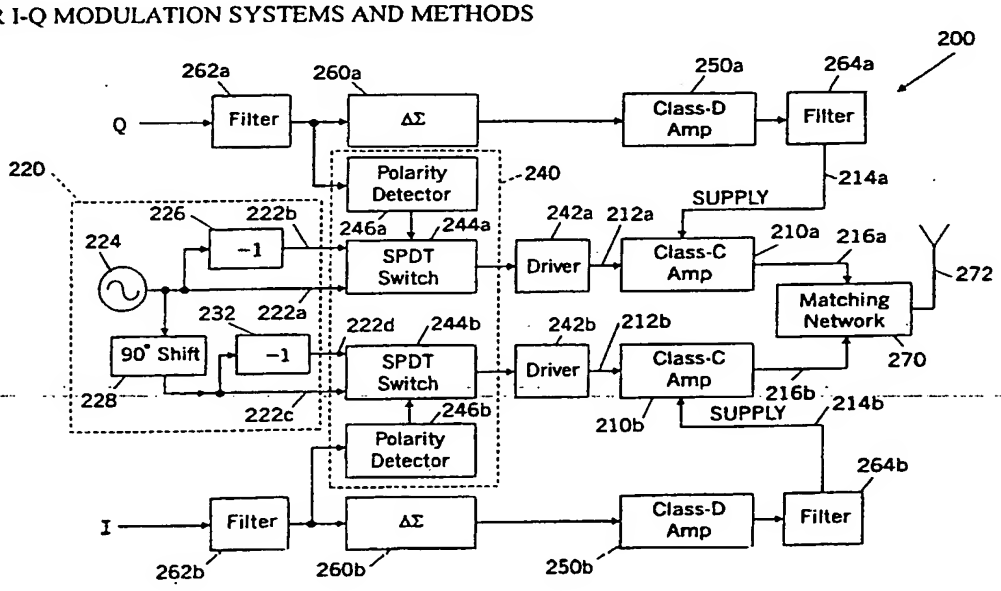

(57) Abstract

Power IQ modulations systems and methods include first and second power amplifiers, each including a signal input, a supply input and a power input. A source of first, second, third and fourth reference frequency signals is also provided. Preferably, the first, second, third and fourth reference frequency signals are 0°, 180°, 90° and 270° phase shifted reference frequency signals, respectively. A switching system applies one of the first and second reference frequency signals to the signal input of the first power amplifier as a function of the polarity of one of the I and Q input signals. The switching system also selectively applies one of the third and fourth reference frequency signals to the signal input of the second power amplifier as a function of the polarity of the other of the I and Q input signals. A third amplifier is responsive to the one of the I and Q input signals to supply a first variable supply voltage to the supply input of the first amplifier. A fourth amplifier is responsive to the other of I and Q input signals to supply a second variable supply voltage to the supply input of the second amplifier. A coupler couples the power outputs of the first and second power amplifiers to a load such as a radiotelephone antenna.

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INTERNATIONAL SEARCH REPORT

Inte ional Application No
PCT/US 99/26913

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H04L27/36 H03C3/38 H03F1/32

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H04L H03C H03F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 778 029 A (KAUFMANN JOHN) 7 July 1998 (1998-07-07) abstract	46,49,51
A	column 2, line 36 -column 4, line 21 figures 4,5	47,48, 50,52
A	US 5 767 750 A (YAMAJI TAKAFUMI) 16 June 1998 (1998-06-16) column 7, line 36 - line 62 figures 2,3,5,25,41	1,16,31
A	US 5 438 301 A (MONTGOMERY ROBERT K ET AL) 1 August 1995 (1995-08-01) abstract column 2, line 31 -column 3, line 43 figure 1	1,16,31

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[X] Further documents are listed in the continuation of box C. [X] Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
15 June 2000	24 07 2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Toumpoulidis, T

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INTERNATIONAL SEARCH REPORT

Int. ional Application No
PCT/US 99/26913

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
A	EP 0 598 585 A (LINEAR MODULATION TECH) 25 May 1994 (1994-05-25) abstract page 2, line 50 -page 3, line 18 claim 1	1-52
A	GB 2 267 402 A (UNIV BRISTOL) 1 December 1993 (1993-12-01) abstract figure 4	1,16,31
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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 99/26913

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This International Search Report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
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3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

see additional sheet

As a result of the prior review under R. 40.2(e) PCT, no additional fees are to be refunded.

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3. ☐ As only some of the required additional search fees were timely paid by the applicant, this International Search Report covers only those claims for which fees were paid, specifically claims Nos.:

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Remark on Protest

☒ The additional search fees were accompanied by the applicant's protest.

☐ No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. Claims: 1-45

   Power I-Q modulation system

2. Claims: 46-52

   System having I-Q predistortion circuit

SDOCID: <WO___0041371A3_I_>

INTERNATIONAL SEARCH REPORT

Information on patent family members

Inte ional Application No
PCT/US 99/26913

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